TBSC-TCR Compensator Simulation: A New Approach in Closed Loop Reactive Power Compensation of Dynamic Loads

Irfan Isak Mujawar, Isak Ismail Mujawar, Swapnil. D. Patil, D. R. Patil, *Member, IAENG*.

Abstract — **Topology for reactive power compensation of dynamic load in closed loop is presented. The scheme consists of Thyristor Binary Switched Capacitor (TBSC) banks and a Thyristor Controlled Reactor (TCR). TBSC is based on a chain of Thyristor Switched Capacitor (TSC) banks arranged in binary sequential manner. TCR capacity is chosen to be smallest of TBSC step size. A transient free switching of TBSCs is carried out. Excessive KVAR given by TBSC is absorbed by TCR. Firing angle range of TCR is selected in such a way that harmonics produced by it are within the safe range. Proposed topology allows stepless reactive power compensation of dynamic load in closed loop. Simulation results show that the proposed scheme can achieve reactive power compensation in cycle by cycle basis and the harmonics content of source are maintained at low level due to filtering action of TBSC.**

Keywords—**Reactive power compensation, TBSC, TCR, transient free switching, Total Harmonic Distortion(THD)**

I. INTRODUCTION

ANY power problem manifested in voltage, current, or frequency deviations that result in failure, misoperation or even damage of customer equipment is considered as a power quality problem [1,2]. Different power quality problems are power frequency disturbances, power system transients, electromagnetic interference, electrostatic discharge, power system harmonics, poor Power Factor (P.F.), grounding & bonding problems etc. [3]. Many big industries, commercial and industrial electrical loads include power transformers, welding machines, arc furnaces, induction motor driven equipment such as elevators, pumps, and printing machines etc., which are mostly inductive in nature. These loads create serious power quality problems. Low Power Factor is the predominant problem now a day. Poor P.F. has various consequences such as increased load current, large KVA rating of the equipment, greater conductor size, larger copper loss, poor efficiency, poor voltage regulation, reduction in equipment life etc. Therefore it is necessary to solve the problem of poor P.F. There are different reactive power compensation techniques to improve the P.F. such as: synchronous condenser, capacitor banks, Static VAR

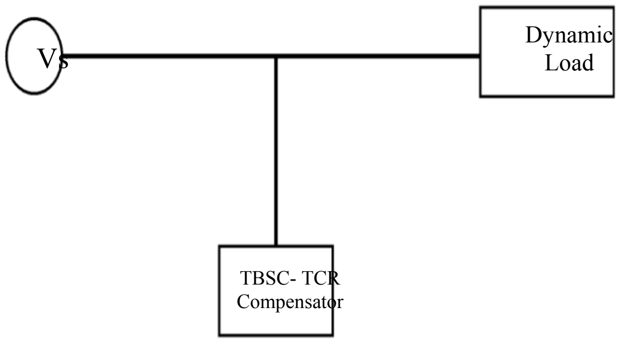

Fig. 1 Proposed Topology

Compensators [4], Self commutated VAR Compensators [5] etc. However, most of them have disadvantages: synchronous machines are bulky, require strong foundation, have a poor dynamic behavior, require significant amount of starting and protective equipment [5], capacitor banks generate high transients during connection & disconnection [6], SVCs are harmonic polluters and controlled semiconductors [Insulated Gate Bipolar Transistors (IGBTs) and Integrated Gate Controlled Thyristors (IGCTs)] used in self-commutated VAR compensators have a limited capacity. Actual semiconductors can handle a few thousands of amperes and have reverse voltage blocking capabilities of 6 to 10 kV, which is not enough for high voltage applications [5]. Also these compensators are expensive.

This paper presents a simple topology, which is shown in Fig. 1. The proposed scheme consists of Thyristor Switched Capacitor (TSC) banks in binary sequential steps [7] known as Thyristor Binary Switched Capacitor (TBSC) operated in conjunction with Thyristor Controlled Reactor (TCR) [8] of the smallest step size. The proposed topology has following distinctive characteristics:
1) Transient free switching of capacitors is carried out. 2) TCR capacity is kept minimum. 3) By coordinating the control between TBSC and TCR, it is possible to obtain fully stepless control of reactive power and we can operate the system at any desired power factor. 4) Reactive power compensation

Manuscript received Jan 27 2014. This work was supported in part by the Electrical Engineering Department of Walchand College of Engineering, Sangli. It is supported under Technical Quality Improvement Program (TEQIP_II).
Irfan I Mujawaris a PG scholor with Electrical Engineering Department of Walchand College of Engineering, Sangli, India. irfanbudhgaon.@gmail.com
Associate.Prof. Isak Ismail Mujawar Department of Electronics and Telecommunication Engineering Nagesh Karajagi Orchid College of Engineering and Technology, Solapur, India. isakmujawar@nkorchidenggmgmt.ac.in
Dr. D.R.Patil is Prof. and Head of Electrical Engineering, Department Walchand College of Engineering, Sangli, India. dadasorpatil@gmail.com.
Swapnil D Patil is a PG scholor with Annasaheb Dange College of Endineering, Ashta, Maharashtra India. swapnil6006@rediffmail.com

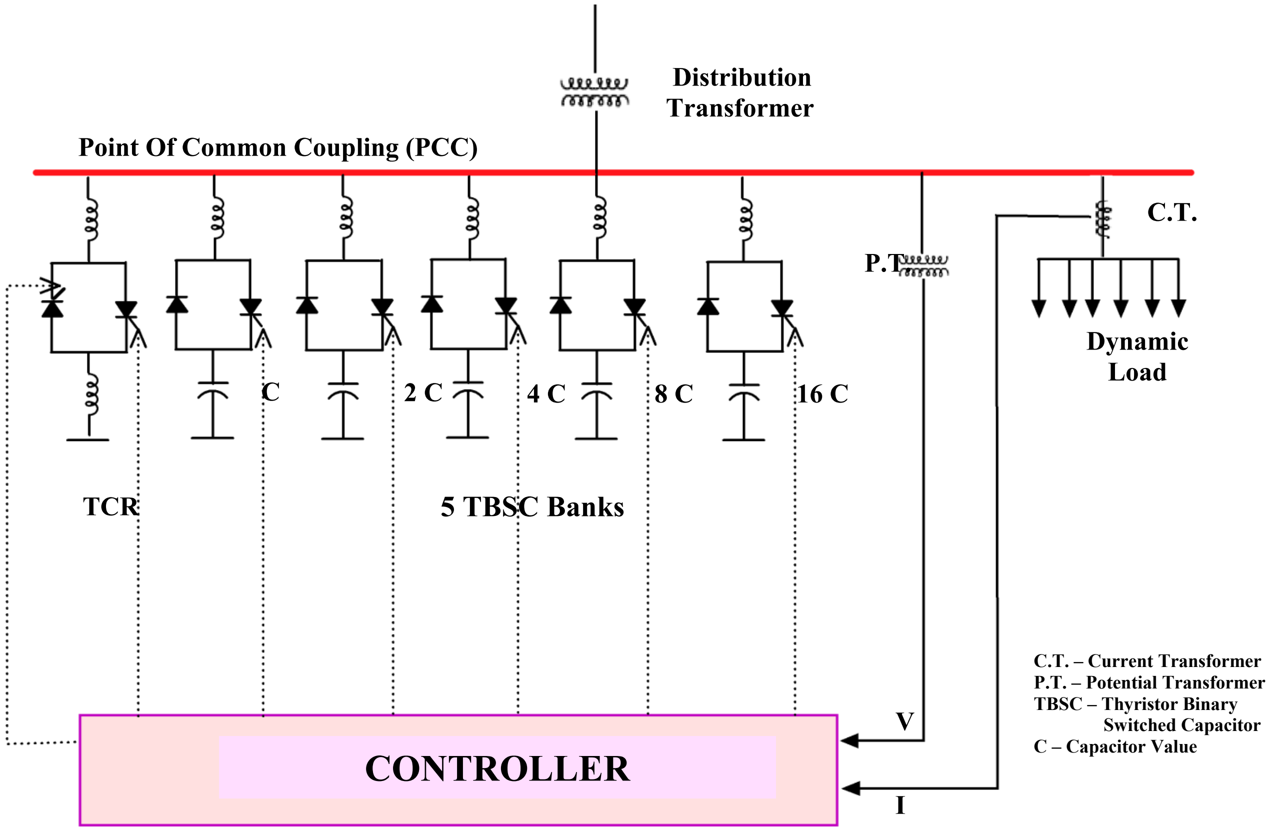

Fig.2 TBSC-TCR Compensator

is achieved in cycle by cycle basis.
This paper is structured as follows. Section II describes the proposed topology. Section III describes the controller in detail. Sections IV and V present simulation results and FFT analysis respectively. Section VI concludes this paper.

II. Proposed Topology Description

TBSC - TCR compensator connected at the point of common coupling (PCC) for reactive power compensation is shown in Fig.2. The operating principle of each equipment is analyzed in the following sections.

A. *TBSC*

TBSC consists of an anti-parallel connected thyristor and diode as a bidirectional switch in series with a capacitor and a current limiting small reactor. Transient free switching of capacitors is obtained by satisfying following two conditions [5]:

a. Firing the thyristors at the negative/positive peak of supply voltage
b. Precharging the Capacitors to the negative/positive peak of supply voltage

TSC current is sinusoidal and free from harmonics, thus eliminating the need for any filters. Small inductor is placed in series with capacitor which in combination with capacitor provides low impedance path for harmonics generated by the associated TCR [9]. In the proposed scheme capacitor bank step values are chosen in binary sequence weights to make the resolution small. If such 'n 'capacitor steps are used then 2^n different compensation levels can be obtained [10]. In this paper five TBSC banks are arranged as 2.5: 5: 10: 20: 40 KVAR in star connected with neutral grounded configuration.

B. *TCR*

A basic TCR consists of an anti-parallel connected pair of thyristor valves in series with a reactor. The anti-parallel connected thyristor pair acts like a bidirectional switch. The TCR acts like a variable susceptance. Variations in the firing angle, α changes the susceptance and, consequently, the fundamental current component I_1 which is shown by equation (1) [9].

$$I_1(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right). \quad (1)$$

Where, V - Peak value of the supply voltage
ω - Angular frequency of supply voltage

Variation in the fundamental current component leads to variation of reactive power absorbed by the reactor. Thus by changing the firing angle of thyristors stepless variation of reactive power can be achieved. If firing angle is increased beyond 900, the current becomes non sinusoidal and odd harmonics are generated [9]. TCR is connected in delta so as to prevent the odd tripplen harmonics from entering into the transmission lines. The inductor in each phase is split into two halves, one on each side of the anti-parallel connected thyristor pair, to prevent the full ac voltage appearing across the thyristor valves and damaging them if a short-circuit fault occurs across the reactor's two end terminals [9]. Binary switched configuration of TSC results into the reduced TCR capacity. Therefore harmonic distortion as well as cost of overall system gets reduced. As minimum capacitor bank step size is 2.5 KVAR, hence TCR of capacity 2.5 KVAR is used.

C. *CONTROLLER*

Controller is the heart of compensator. Voltage V and current I at PCC is sensed by Potential Transformer (P.T.) & Current Transformer C.T. respectively and given to controller. Controller calculates the value of reactive power required to achieve the desired power factor & then generates the control signals (gate signals) which are given to TBSC banks and TCR. By coordinating the control between TCR and TBSC, it is possible to obtain fully stepless control of reactive power in closed loop.

III. CONTROLLER DESCRIPTION

A. *TBSC Closed Loop Operation*

A block diagram of reactive power compensator using TBSC banks is shown in Fig. 3. Reference reactive power, Q_{Ref} is calculated from the desired power factor. Actual reactive power at PCC, Q_{Actual} is calculated by sensing voltage and current at PCC by P.T. and C.T. respectively. Error between Q_{Ref} and Q_{Actual} is given to PI Controller. Here Discrete PI Controller is used. Output of PI Controller is given to ADC. Output of ADC is given to TBSC banks in such a way that no transients occur. In this way closed loop operation of TBSC banks for reactive power compensation is achieved.

B. *TCR Closed Loop Operation*

A block diagram of reactive power compensator using TCR is shown in Fig. 4. Reference reactive power, Q_{Ref} is compared with the actual reactive power at PCC, Q_{Actual}. The error signal is converted to the TCR firing angle using lookup table method. In this way closed loop operation of TCR for reactive power compensation is achieved.

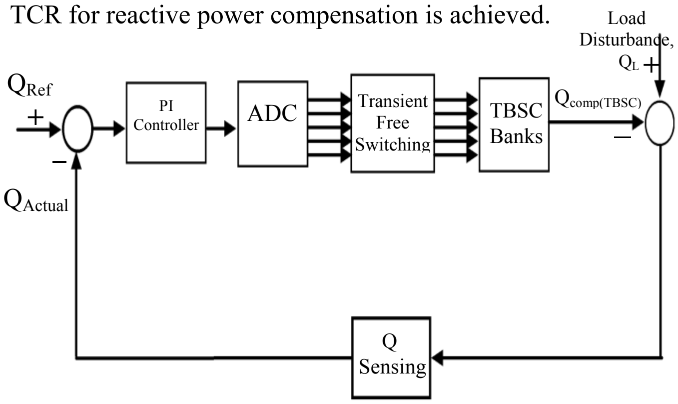

Fig. 3 TBSC closed loop operation

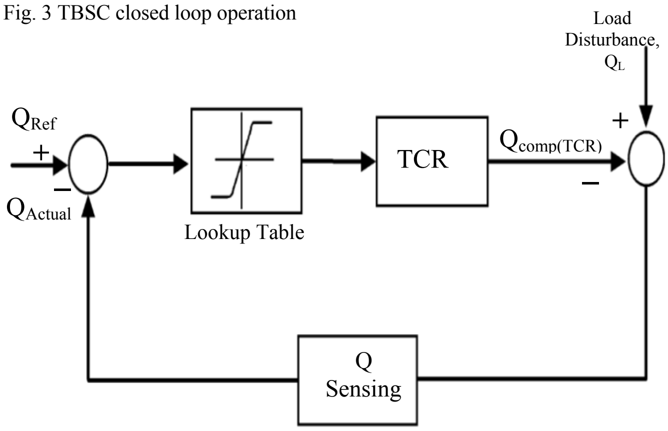

Fig. 4 TCR closed loop operation

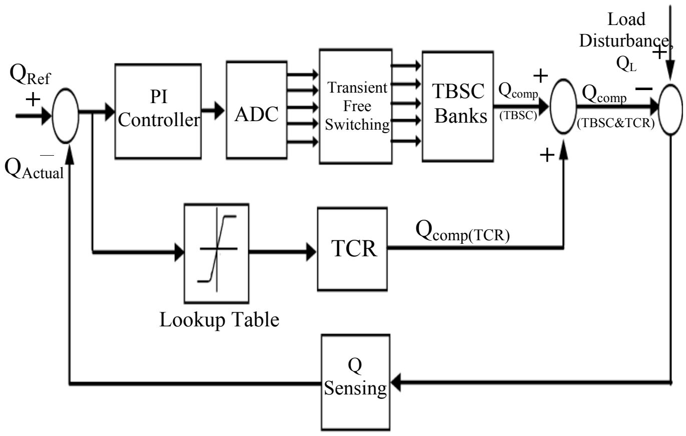

Fig. 5 Reactive power compensator using TBSC-TCR

C. *TBSC-TCR Compensator Closed Loop Operation*

A block diagram of reactive power compensator using TBSC-TCR is shown in Fig. 5. Due to binary switched arrangement of TSCs, reactive power supplied by TBSC $Q_{comp(TBSC)}$ may be greater than the required load reactive power Q_L. This may lead to leading P.F. To avoid this, excess leading KVAR is given to the TCR controller which generates the firing pulses according to the received input signal using lookup table method. Thus excess leading KVAR is absorbed by TCR. At all times reactive power given by combination of TBSC & TCR, $Q_{comp.(TBSC\&TCR)}$ closely follows Q_L. In this way closed loop operation of TBSC-TCR compensator for reactive power compensation is achieved.

IV. SIMULATION RESULTS

MATLAB/SIMULINK is used in the paper for simulation. Data used in Simulation is shown below.

a. Source:-
   Voltage V = 400 V, Rs = 0.0287Ω, Ls = 0.20471mH
b. TCR:- Each coil have R = 9Ω and L = 300 mH
c. TBSC banks:-
   Five TBSC banks are used in the simulation whose values are shown in Table I.

TABLE I. VALUES OF FIVE TBSC BANKS

Sr. No.	Q (in KVAR)	C (in µF)	L (in mH)
1.	2.5	47	0.2155
2.	5	94	0.1077
3.	10	188	0.0538
4.	20	376	0.0269
5.	40	752	0.0134

ISBN: 978-988-19253-3-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

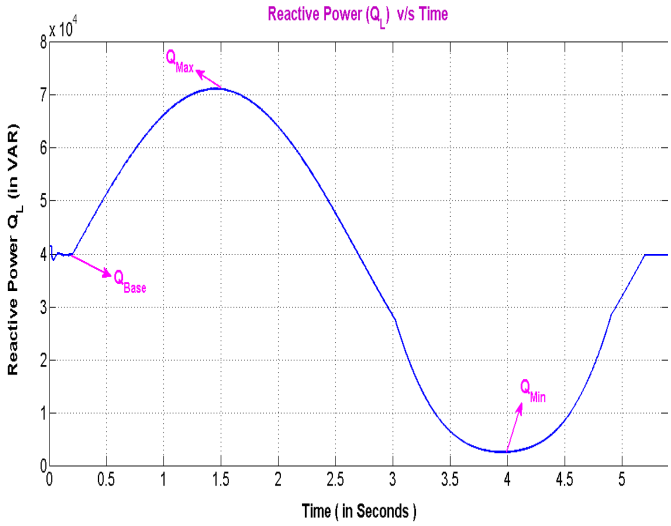

Fig.6 Simulation result of three phase dynamic load.

Continuously changing reactive power, Q_L is obtained by simulating three phase dynamic load. Typical nature of load variation is shown in Fig.6. Minimum reactive power Q_{min}, maximum reactive power Q_{Max}, and base reactive power Q_{Base} can be varied by changing the parameters of three phase dynamic load. In all simulations Q_{Ref} is set to zero since it is assumed that desired P.F.is unity at all times.

A. *TBSC Closed Loop Operation*

Discrete PI controller with $K_P = 0.565$ & $K_I = 25$ is used. 5 bit ADC is used in simulation. Parameters of Three-phase dynamic load block are adjusted in such a way that Q_L varies continuously from $Q_{Min.} = 2.5$ KVAR to $Q_{Max.} = 71.5$ KVAR with base load $Q_{Base.} = 40$ KVAR. Waveforms of load reactive power Q_L, reactive power given by TBSC, $Q_{comp.(TBSC)}$ and actual reactive power Q_{Actual} at PCC are shown in Fig. 7. From simulation results it is seen that $Q_{comp.(TBSC)}$ closely follows Q_L and actual reactive power Q_{Actual} at PCC is approximately zero at all times. The small error is due to the binary switching arrangement of TSCs. Current waveforms through all TBSC banks & source (of R phase) are shown in Fig. 8 which shows that neither transients nor harmonics occur.

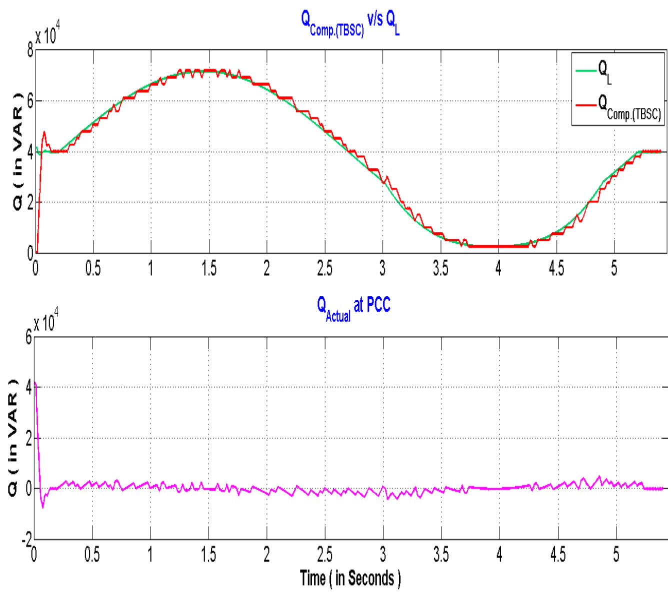

Fig. 7 Simulation results of closed loop operation using TBSC

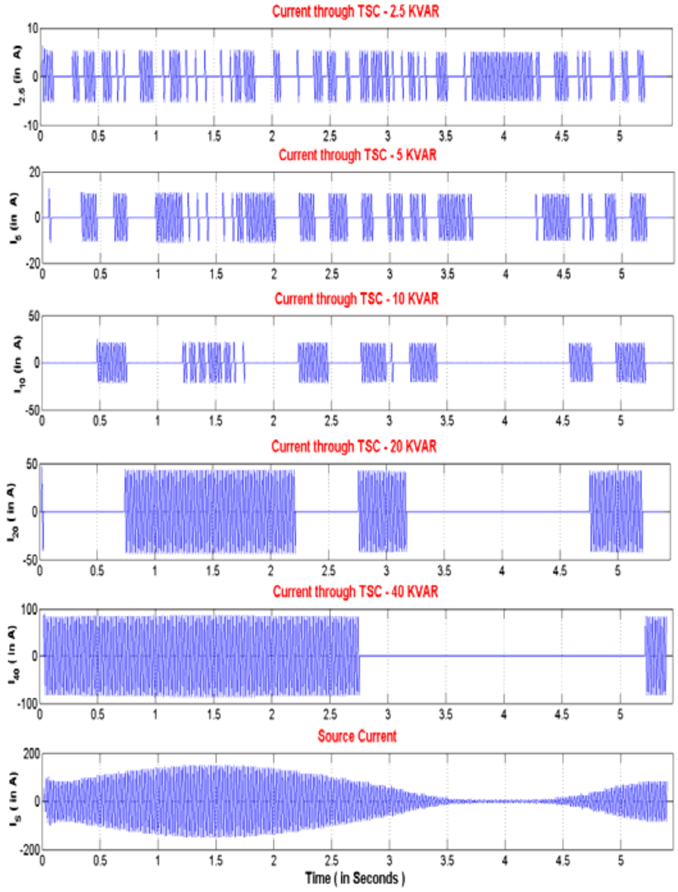

Fig. 8 Current Waveforms through all TBSC banks & Source (of R phase only)

B. *TCR Closed Loop Operation*

Parameters of Three-phase dynamic load block are adjusted in such a way that Q_L varies continuously from $Q_{Min.} = 260$ VAR to $Q_{Max.} = 2500$ VAR with base load $Q_{Base.} = 1500$ VAR. Waveforms of load reactive power Q_L, reactive power given by TCR, $Q_{comp.(TCR)}$ and actual reactive power Q_{Actual} at PCC are shown in Fig. 9. From simulation results it is seen that $Q_{comp.(TCR)}$ closely follows Q_L and actual reactive power Q_{Actual} at PCC is approximately zero at all times.

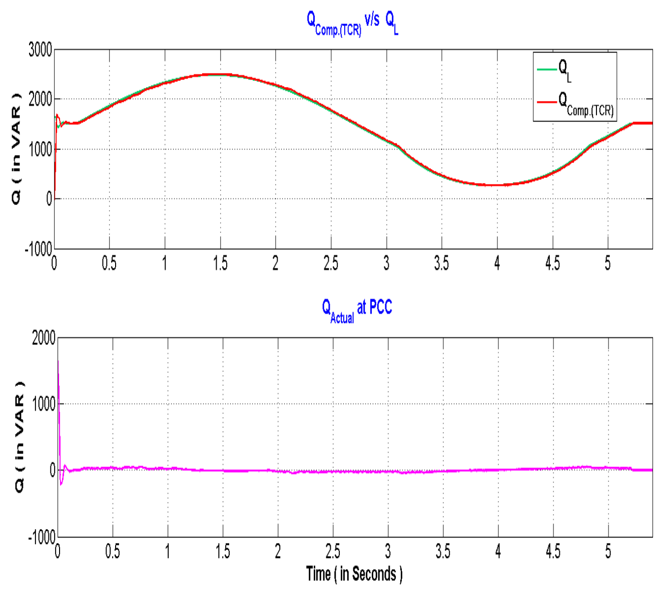

Fig. 9 Simulation results of closed loop operation using TCR

ISBN: 978-988-19253-3-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

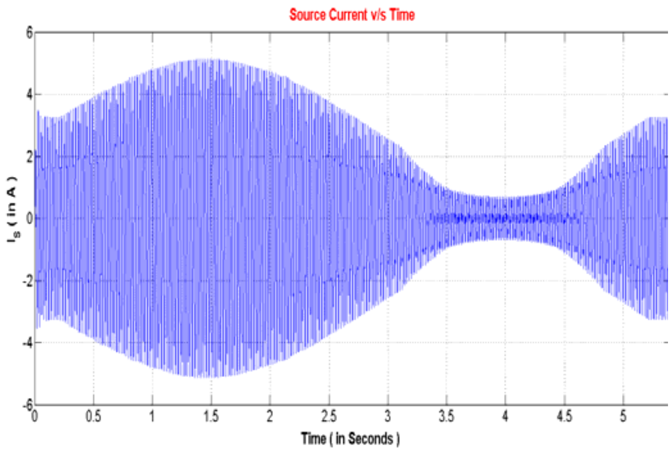

Fig. 10 Current waveform through source (of R phase only)

Current waveform through source (of R phase) is shown in Fig. 10. Table II shows for various firing angle α, the fundamental line and phase currents $I_1(\alpha)$ in ampere, $\%THD_I$ values in line and phase and reactive power Q in VAR. From Table II it can be concluded that,

a. Reactive power Q can be varied by changing the firing angle α.

b. THD_I values in line are less than that of phase. This is due to the fact that all triplen harmonics get circulated through phase and they do not enter into the line side because of delta connection of TCR.

c. As the firing angle α approaches to 180^0, the THD_I goes on increasing. It is observed that the safest region of TCR operation without significant harmonics is in between 85^0 to 140^0. This firing angle range is used in the paper to avoid the large harmonic distortion. TCR will provide reactive power compensation from 260 VAR to 2500 VAR in stepless manner.

TABLE II. SIMULATION RESULTS OF TCR

Sr. No.	α in Degrees	Q in VAR	% THD $_I$		$I_1(\alpha)$	
			Line	Phase	Line	Phase
1	85	2500	0.63	1.11	3.53	2.04
2	95	1780	9.27	16.69	2.58	1.48
3	105	1514	11.48	23.46	2.19	1.26
4	115	975	10.48	39.41	1.41	0.81
5	125	685	11.66	51.98	0.99	0.57
6	135	358	26.30	75.78	0.51	0.29
7	145	172	54.89	106.71	0.24	0.14
8	155	43	152.93	214.45	0.06	0.035

C. TBSC-TCR Compensator Closed Loop Operation

When $Q_{comp(TBSC)}$ supplied by TBSC is greater than the required load reactive power Q_L and if difference between them is greater than 260 VAR then TCR will come into the action. TCR controller will generate the firing pulses according to the error signal between $Q_{comp(TBSC)}$ and Q_L. Thus excessive leading VAR gets absorbed by TCR and actual reactive power at PCC, Q_{Actual} is maintained close to the Q_{ref} (here Q_{ref} is zero as already mentioned).

Waveforms of load reactive power Q_L, reactive power given by TBSC-TCR, $Q_{comp.(TBSC\ \&\ TCR)}$ and actual reactive power Q_{Actual} at PCC are shown in Fig. 11. From simulation results it is seen that $Q_{comp.(TBSC\&TCR)}$ closely follows Q_L and Q_{Actual} at PCC is very close to zero at all times. Difference between $Q_{comp.(TBSC)}$ and Q_L is the reference reactive power $Q_{TCR\text{-}Ref}$ for TCR. Waveforms of $Q_{TCR\text{-}Ref}$ and actual reactive power given by TCR, $Q_{comp.(TCR)}$ are shown in Fig. 12. From Fig. 12 it is seen that $Q_{comp.(TCR)}$ closely follows $Q_{TCR\text{-}Ref}$. Maximum reactive power absorbed by TCR is 2500 VAR. Thus TBSC-TCR compensator can provide reactive power compensation from 260 VAR to 77.5 KVAR in steles manner.

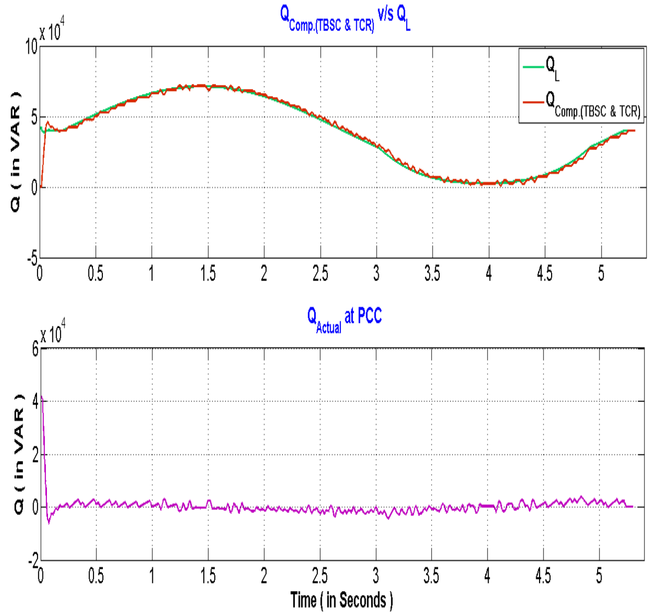

Fig. 11 Simulation results of closed loop operation using TBSC & TCR

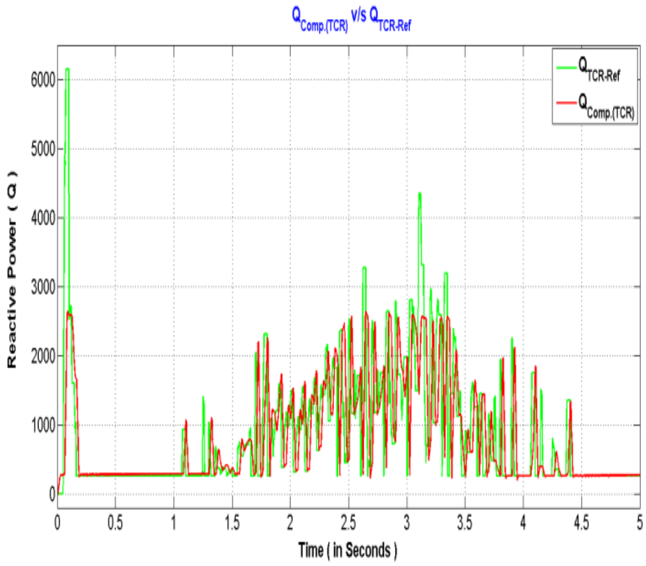

Fig. 12 Waveforms of $Q_{comp.(TCR)}$ v/s $Q_{TCR\text{-}Ref}$

ISBN: 978-988-19253-3-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

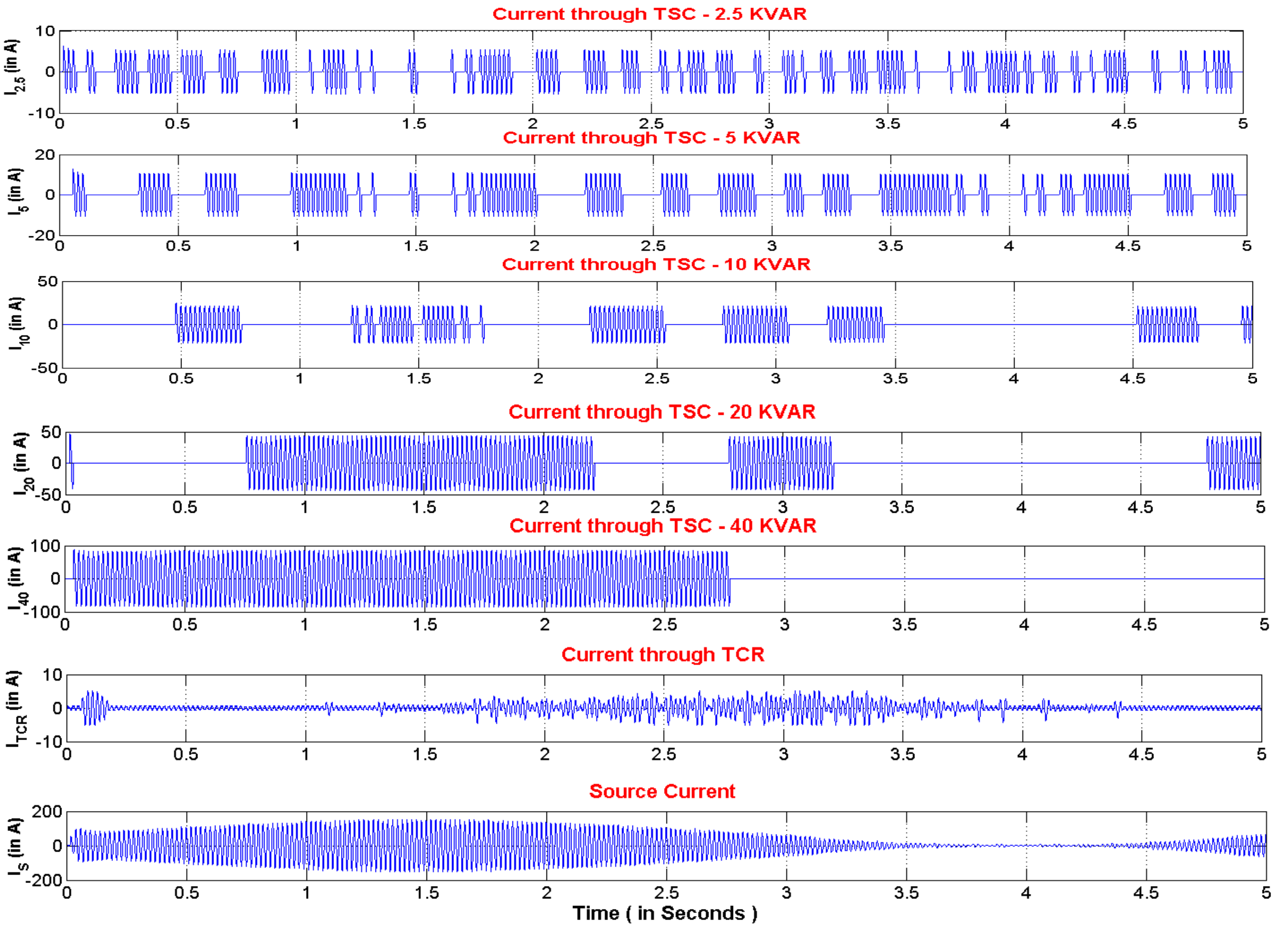

Fig. 13 Current Waveforms through all TBSC banks, TCR & source (of R phase only)

Current waveforms through all TBSC banks, TCR & source (of R phase) are shown in Fig. 13 which shows that no transients are absent.

V. FFT Analysis

FFT analysis is performed for the combined operation of TBSC and TCR. For maximum firing angle (140^0) of TCR, values of $(THD)_I$ for TCR current and source current are shown in Fig. 14 and 15 respectively.

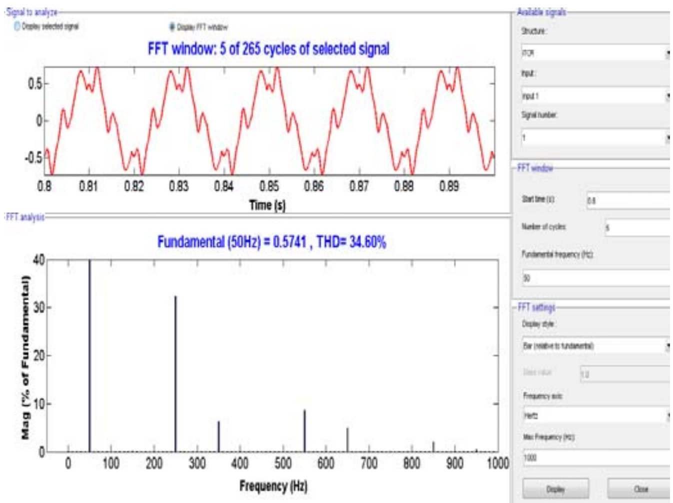

Fig. 14 FFT analysis for TCR current

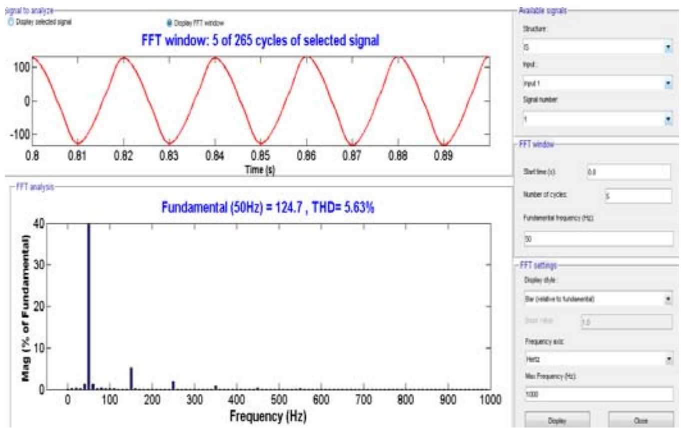

Fig. 15 FFT analysis for source current

From Figures it is seen that even though THD for TCR current is 34.60%, it gets filter out and reduces to 5.63% towards the source side. This is due to the fact that harmonics produced by TCR gets bypassed through five TBSC banks in parallel.

VI. Conclusion

A combined topology, using a TBSC and TCR has been presented. The TSC bank step values are chosen in binary sequence weights to make the resolution small and to reduce the capacity of TCR. Current flowing through TBSC, TCR as well as source is transient free. Harmonic content in source current is negligibly small. By coordinating the control between TBSC and TCR, it is possible to obtain fully stepless control of reactive power. Also one can operate the system at any desired power factor. Proposed topology can compensate for rapid variation in reactive power in cycle by cycle basis. Controller used is very simple and reliable. Compared with other topologies able to do the same work, the presented topology is more economical, because thyristors are used which are cheaper than IGBTs and IGCTs. The results obtained, shows an excellent behavior under both steady-state and transient conditions. The proposed scheme can be implemented where there are fast variations in reactive power such as arc furnaces, welding equipments etc.

REFERENCES

[1] Roger C. Dugan, Mark F. McGranaghan, Surya Santoso and H. Wayne Beaty: ElectricalPower Systems Quality. 2nd edition, McGraw-Hill Companies(2004)

[2] R. SastryVedam and Mulukutla S. Sarma: Power Quality - VAR Compensation in Power Systems.CRC press, Taylor and Francis Group (2009).

[3] C.Sankaran:Power Quality.CRC press (2002)

[4] Juan Dixon,Yamilledel Valle, et al.: A Full Compensating System for General Loads, Based on a Combination of Thyristor Binary Compensator, and a PWM-IGBT Active Power Filter, IEEE Trans. Industrial Electronics, vol. 50, no. 5,pp. 982-989.(2003)

[5] Juan Dixon, Luis Morán, José Rodríguez, Ricardo Domke, “Reactive Power Compensation Technologies, State of- the-Art Review”, proceedings of the IEEE, vol. 93, no. 12, pp. 2144-2164, 2005.

[6] L. Smith: A Practical Approach in Substation Capacitor Bank Applications to Calculating, Limiting and Reducing the Effects of Transient Current.IEEE Trans. Ind. Application., vol. 31, pp. 721–724.(1995)

[7] C. Maffrand, J. W. Dixon, and L. Morán: Binary Controlled, Static VAR Compensator, Based on Electronically Switched Capacitors. In: Proc. IEEE PESC’98, pp. 1392–1396. (1998).

[8] D. R. Patil and U. Gudaru: FiringAngle Range Control for Minimising Harmonics in TCR Employed in SVC’s.World Academy of Science Engineering and Technology 80, pp.109–118. (2011).

[9] R.MohanMathur and Rajiv K. Varma:Thyristor-Based FACTS Controllers for Electrical Transmission Systems, a John Wiley and sons, Inc. Publication (2002).

[10] U. Gudaru and D. R. Patil: An Innovative Transient Free Adaptive SVC in Stepless Mode of Control, World Academy of Science Engineering and Technology77, pp.200–207. (2011).

AUTHOR BIOGRAPHY

Irfan Isak Mujawar has obtained his B.E. Electrical and M.Tech Electrical (Power Systems) in first class with distinction both from Walchand College of Engg. Sangli, India in 2009 and 2013 respectively. He stood first in the college during his M.Tech. Currently he is working as Assistant Professor in department of Electrical engineering in Nagesh karajagi Orchid College of Engineering and technology, Solapur. His areas of interest include FACTS, power electronics and power quality.

Isak Ismail Mujawar has obtained his M.Sc. and M.E. both in Electronics in first class with distinction in 1984 and 2007 respectively from Shivaji University, Kolhapur (India) and stood first in the college. Currently he is working as Head of Depertment of Electronics and telecommunication engg. in Nagesh karajagi Orchid College of Engineering and technology, Solapur. His areas of interest include digital and analog design and power electronics.

D. R. Patil aged 57 has obtained his B.E. (Electrical) in first class in 1981, M.E. (Electrical) in first class in 1985 and Ph.D. in 2012 from Shivaji University, Kolhapur. He started his teaching career from 1985, as a lecturer in Electrical department of Walchand College of Engineering, Sangli (India). Subsequently in 1993 he promoted as assistant professor of control systems on the post graduate. He has been actively associated with teaching various subjects of control systems as well as power systems at post graduate levels. He has guided almost 70 dissertation / project at post graduate level and about 30 projects at under graduate levels. He has about 20 international conference and 15 national conference / seminars publications. He conducted 3 workshops and 3 training programs in the institute. Also, he has attended 12 summer / winter schools. His areas of interest are control systems applicable to power systems.

Swapnil D. Patil aged 23 has obtained his B.E. in Electrical Engineering with First Class in 2013 from Shivaji University, Kolhapur (MS). He is pursuing his post graduation from Shivaji University Kolhapur. His areas of interest are Power System, FACTS and Power Quality.

ISBN: 978-988-19253-3-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)